AGILE SUB-ICE GEOLOGICAL DRILL

Operations and Maintenance Manual

July 25, 2019

U.S. Ice Drilling Program
University of Wisconsin-Madison Space Science & Engineering Center

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1.0 PURPOSE

This document describes the operations and maintenance of the Agile Sub-Ice Geological (ASIG) Drill System.

2.0 SCOPE

This document applies to the operations and maintenance of the ASIG Drill System including all major field-deployable drill sub-systems.

3.0 REFERENCES

1008-0014 SSEC Project Safety Plan
8323-0003 ASIG Science Requirements
8323-0004 ASIG Engineering Requirements
8323-0005 ASIG Failure Mode and Effects Analysis
8323-0010 ASIG North American Test Report
8323-0019 ASIG Safety Training
8323-0020 ASIG Equipment Manuals
8323-0021 ASIG Rig Assembly Drawings
8323-0022 ASIG Safety Data Sheets
8323-0023 ASIG Equipment Lists

4.0 DEFINITIONS

4.1. ASIG – Agile Sub-Ice Geological

4.2. IDP – U.S. Ice Drilling Program, formerly IDDO

4.3. MPP – Multi-Power Products, ASIG Drill Rig Manufacturer

4.4. NA – North American

4.5. PSL – Physical Sciences Laboratory

4.6. QAS – Quality Assurance and Safety group

4.7. SSEC – University of Wisconsin-Madison, Space Science & Engineering Center

5.0 RESPONSIBILITIES

5.1. IDP Engineering is responsible for the generation and maintenance of this document.

5.2. SSEC QAS is responsible for ensuring that this document is created, reviewed, approved, maintained and changed per applicable SSEC processes.

5.3. Project personnel are responsible for understanding this document.

6.0 RECORDS

None.

7.0 Safety

The SSEC Project Safety Plan, 1008-0014, provides an overview of the approach to safety on projects and applies to IDP equipment and field projects. All drillers operating or assisting in operation of the ASIG Drill System must read and understand the following:

- General Machine and Personnel Safety Section in the MPP 'Man Portable Drill Owner's Manual' (See 8323-0020 ASIG Equipment Manuals).
- 8323-0019 ASIG Safety Training.

8.0 System Operations Overview

Only IDP trained and approved drillers may operate the ASIG Drill system due to safety and operational risks.

Detailed performance data for the rig is summarized in Appendix B.

8.1. Drill Rig

Figure 1 shows major components of the drill rig. See 8323-0020 ASIG Equipment Manuals for complete rig operations manual.

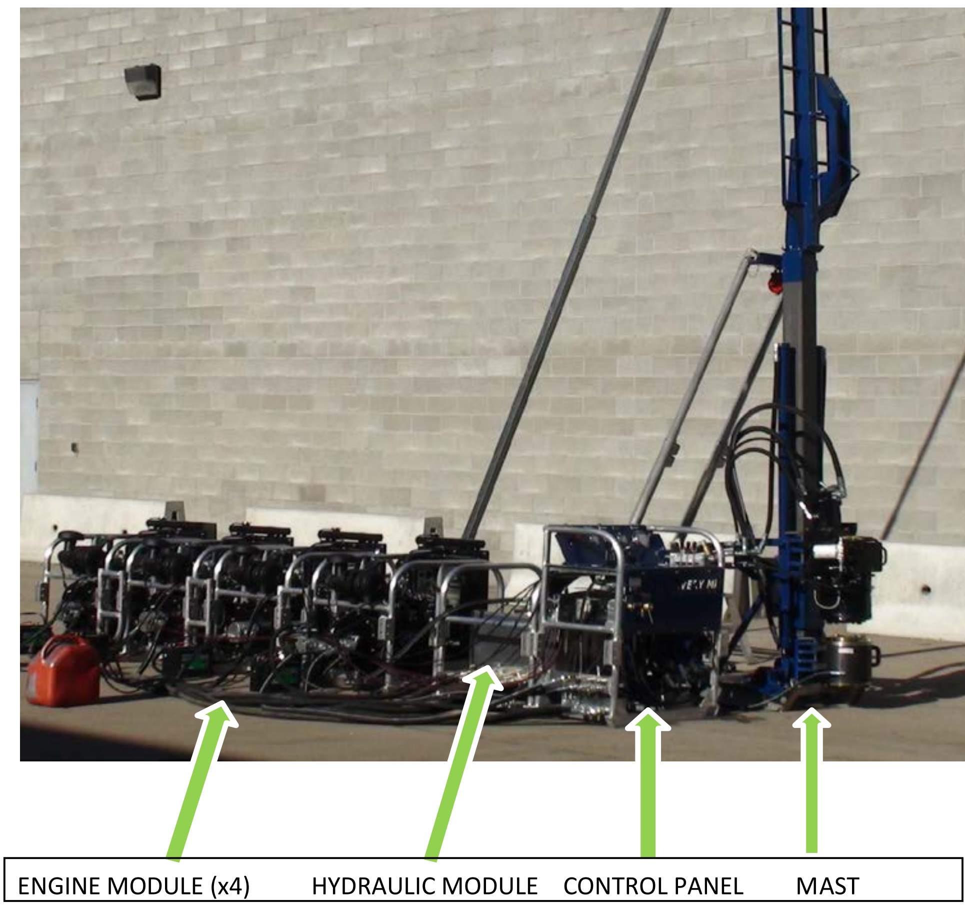


Figure 1: Drill Rig Overview

8.2. Pilot Hole and Casing Setting Systems

Detailed drawings of the packer can be found in 8323-0021 ASIG Equipment Assembly Drawings. Figure 2 provides an overview of the packer assembly used to seal the casing to the borehole wall.

Important Note:

- *Formation Pressure Limits: Both drill fluid circulation pressure and packer inflation pressure have the potential to crack the formation resulting in a loss of effective circulation. Typical values for pressure limits are: 100psi maximum drill fluid circulation pressure limit and 250psi packer pressure (inflated with drill fluid, the packer should be a minimum 100psi over max borehole pressure). The actual limit values will be site-dependent. Set the mud pump relief valve to help ensure the drill fluid circulation pressure limit is not exceeded. Packer pressure should initially be verified frequently.*

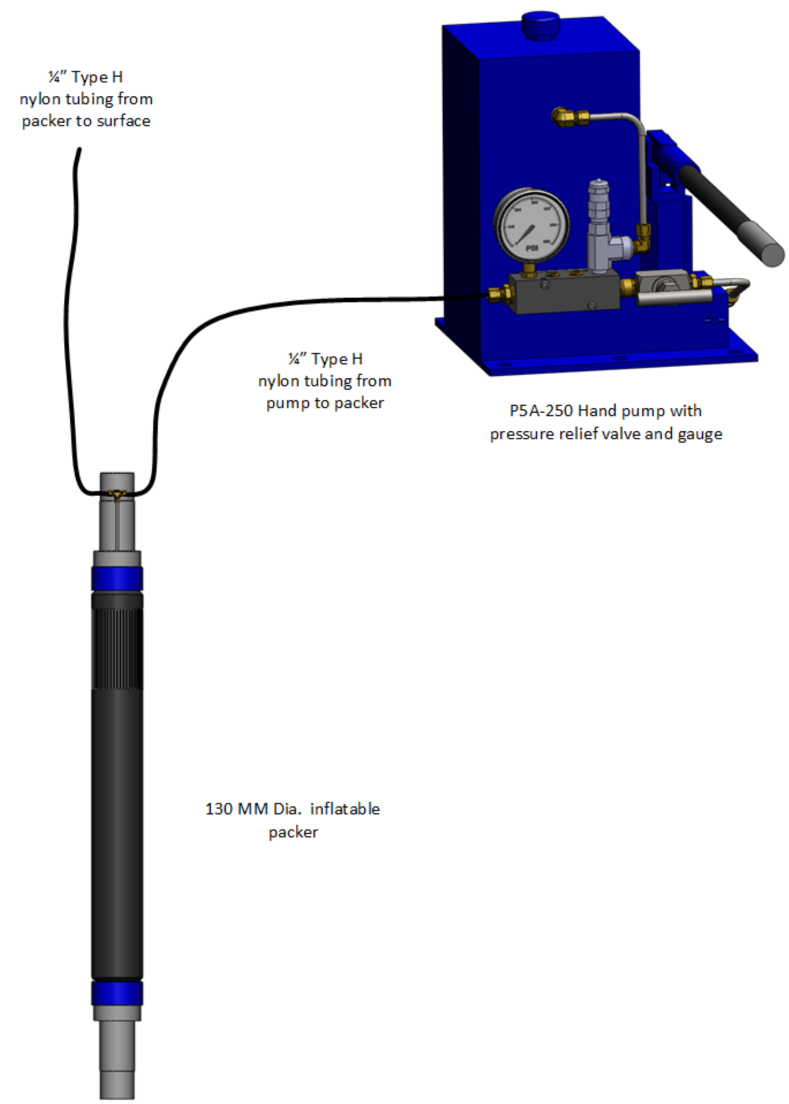


Figure 2: Hand Pump and Packer Diagram

8.2.1. Packer, Casing, and Diverter Installation Procedure, Figure 3.

1. Connect two ¼" Nylon inflation lines to the packer using the brass tee fitting. Fix the lines to the casing tube with a hose clamp, making sure the bends in the lines do not stick out beyond the diameter of the packer.

Figure 3: Installing dual inflation lines at the tee above the packer

2. Be sure the inflation lines are not filled with fluid.
3. Cap one inflation line and connect the other line to the air compressor.
4. Pressurize the system and check for leaks.
5. Remove the pressure from the system and deflate the packer.
6. Fit the head and foot clamps with jaws for the 3" casing.
7. Install the casing to packer adapters on both ends of the packer.
8. On the down side of the packer, install a drill lead in shoe. This is the fitting with the tapered lead on the inside to prevent the drill head reamer shells from catching the end of the casing.
9. Place the Kwik Klamp on the pipe stub at the top of the packer.
10. Lower packer into the borehole and rest the Kwik Klamp on dunnage placed at the surface (foot clamp my need to be swung out of the way while lowering the packer.
11. Feed a 3m section of casing through the head and foot clamps and thread it onto the packer.
12. With the casing section held in the head and foot clamps, remove the Kwik Klamp.

13. Casing centralizers should be spaced on the casing per the following table to achieve the desired buckling capacity.

Compression Load Limit (lbs.) (2x SF)	Required Centralizer Spacing (m)
5,000	3.3
7,500	2.7
10,000	2.3

14. Determine the desired centralizer spacing and lower the casing so the centralizer can be installed just below the foot clamp.
15. Install the centralizer.
    a. Install the clamp ring by tightening the set screws.
    b. Fit the centralizer over the clamp ring. The centralizer should be free to rotate and move up and down on the casing until it contacts the stop ring.
16. Do not fix the packer inflation lines to casing. Doing so may cause the centralizers to damage the lines if the casing needs to be rotated to position the diverter.
17. Make sure the inflation lines do not get pinched between the centralizer blades and the borehole wall as the casing is lowered.
18. Using thread grease, continue adding casing sections and centralizers until the packer has reached the desired depth.
19. Position the last casing joint just below the foot clamp.
20. Place dunnage across the sump well and install the Kwik Klamp on the casing.
21. Remove the upper section of casing going through the head and foot clamps.
22. Swing the foot clamp out of the way and raise the head.
23. Install the diverter assembly and sump liner onto the casing. Be sure to rotate the fitting on the side of the diverter to as close to the final position as possible.
24. Install the casing hoist plug in the head and rig the diverter to the head using lifting straps.
25. Raise the head and lift the casing string enough to remove the Kwik Klamp.
26. Rotate the diverter and casing string to the desired alignment.
27. Lower the assembly until the holes in the diverter struts line up with the holes in the rig base.
28. Bolt the diverter mount struts to the rig base and adjust the struts as necessary to get the sump liner to fit properly.
29. Hook up one of the packer inflation lines to the hand pump and leave the other line open.
30. Fill the hand pump with Isopar K and begin pumping fluid into the lines. Continue pumping fluid until the return line flows bubble free fluid.
    a. The hand pump tank will have to be filled with fluid several times to fill the lines and packer.

   b. Be sure to not let the level in the tank get too low or air will be pumped into the system.

31. Cap the return line.
32. Inflate the packer to the desired pressure. Note: The pressure relief valve on the hand pump is set to 750 psi.
33. You may have to periodically bump the pressure back up until the fluid temperature stabilizes. The fluid volume decreases as it cools, which cause the pressure to drop, and may initially look like there is a leak.
34. Close the silver handled valve on the pump manifold.

8.2.2. Packer Deflation and Casing Removal

1. Release the pressure by opening the needle valve and pump valves.
2. Remove the cap on the return line and disconnect the line from the hand pump. Fluid may continue to slowly come out of the lines, so have a catch container handy.
3. Connect the air compressor to the end of one of the lines and turn on.
4. Run the compressor until mostly air is coming from the other line.
5. Remove the line from the compressor and let the system rest for ~10 minutes.
6. Connect the compressor to the system and pressurize again. More fluid should come out of the open line.
7. Let the system rest again.
8. Connect the rig head to the diverter as was done for the installation.
9. Unbolt the diverter and try pulling up the casing. If it doesn’t come easily, repeat steps 3 – 5 again. This should remove more fluid from the system so the packer can further deflate.
10. Repeat these steps as needed to get the packer to release.
11. Remove the diverter and casing in reverse order from how it was installed.

8.3. Fluid Circulation and Filtration

Figures 4 and 5 provide a description of the circulation and filtration assemblies. Detailed performance data for the circulation system is summarized in Appendix B.

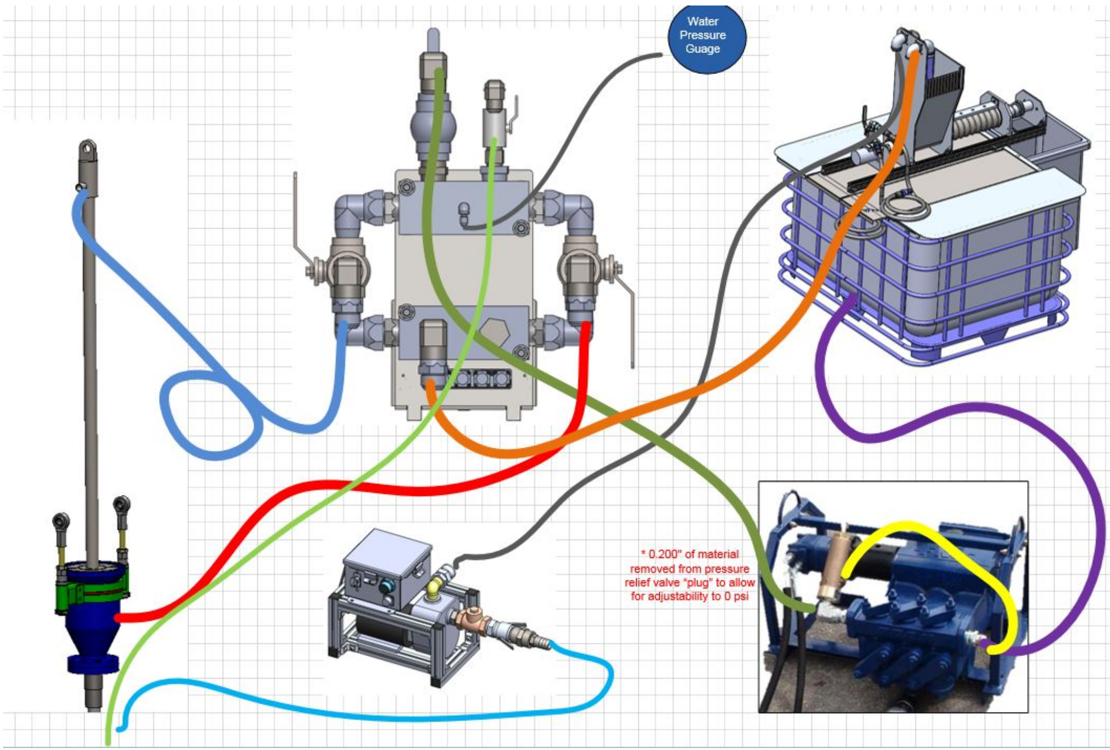


Figure 4: Circulation and Filtration Schematic

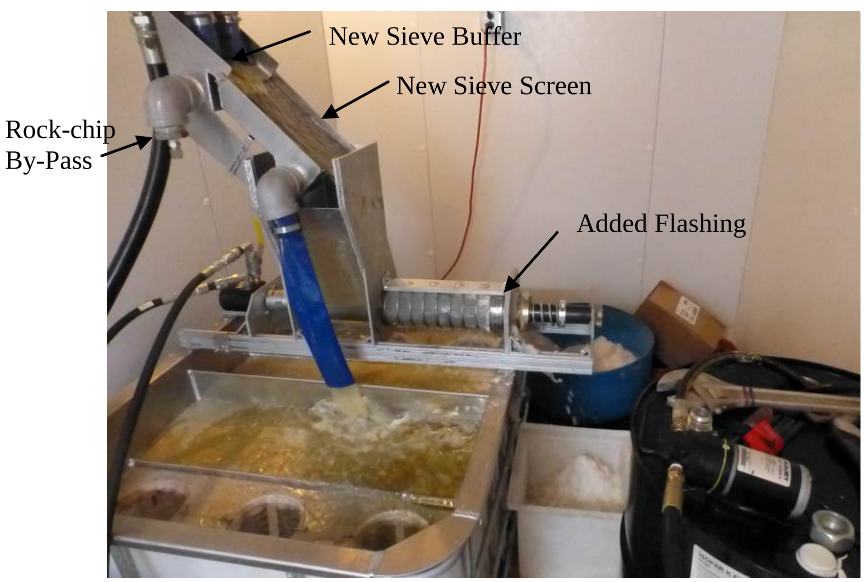


Figure 5: Chip Auger

A light spring force should be used at the chip auger outlet cone (spring length 3.75" with the cone fully closed). Based on previous testing, heavier spring forces result in risk of auger clogging with only minimal benefits in chip to fluid ratios.

The amount of fluid entering the hopper can be adjusted by changing the angle of the screen sieve. The most nearly horizontal position was best at 12gpm in testing.

Ice chips are discharged with a drill fluid content of 20% to 25% melted vol. (16% to 20% wt.). Further fluid recovery can be achieved by moving processed chips to the melter tank.

Rock cuttings should be released directly into the bag filters through the chip by-pass to reduce wear on the ice chip auger.

8.4. Downhole Tooling

The ASIG System uses Sandvik TK56 metric thin-kerf rod and coring assembly. The following manuals describing operating parameters and proper use of this equipment are included in 8323-0020 ASIG Equipment Manuals.

- Sandvik TK56 Systems Users Guide
- Sandvik - Care and Handling of Wireline Drill Rods
- Hagby Recovery Kit Users' Manual - Sandvik
- Sandvik Guide to Mineral Exploration Revised for ASIG

See 8323-0010 ASIG NA Test Report for detailed results of testing of the ASIG System in rock, ice and sediment laden ice drilling. The following summarizes successful operating parameters identified in testing.

Ice Access Hole

An IDP-designed bit with 30° rake cutters has been successfully tested for full-hole drilling in solid ice, Figure 6. Penetration rates from 0.06 – 1.92 m/s, at rotational speeds from 100 – 200 RPM, were achieved with reverse-circulation and continuous filtration. The rate of penetration was set by the rig and thus the weight-on-bit (WOB) was kept to essentially zero. Pump speeds from 2.5 to 6.5 (on the control console Water Pump knob) were used, with less tendency for chip clogs to form (pressure spikes) with higher flows. The pressure of the circulating fluid when drilling was generally below 20 psi.

Figure 6: ASIG Ice Cutter Head
Custom ice drilling head shown with one of three cutters in position

Ice Coring

Coring and recovery of ice cores was demonstrated with the PCD Coring Bit (#5422) from Scorpion Engineering drilling at 100 RPM, with a rate-of-penetration (ROP) of 0.18 m/s and the fluid pump set at position 3 ½ with normal-circulation. The fluid pressure remained 60-80 psi during the run.

Rock Coring

Rock cores were recovered in both concrete and granite with the best results coming from the #12 matrix hardness Impregnated Coring Bit (#4821), Figure 7 (left). ROP varied from 1 – 4 mm/s with rotation speed at 500-800 RPM. Target Head Torque was approximately 1500 psi. Fluid pressure was 60-90 psi while coring with normal circulation (pump pos. 3 ½). There were some signs of bit burning, which may have been caused by excessive WOB or insufficient fluid flow (i.e. cooling).

Solid granite and concrete was also successfully cored with the QD Tech Hybrid Coring Bit (#90513), Figure 7 (right). However, 10 cm of granite and 30 cm of concrete wore the leading edge of each cutter flat so that no clearance angle remained to cut ice or soft sediment.

Figure 7: Coring Bits - At left, Diamond-impregnated coring bit; at right, worn QD Tech Hybrid coring bit for mixed ice/rock coring.

Mixed Rock and Ice Coring

Coring of granite chunks (0.5 – 2 cm) frozen in ice was conducted with the GeoSet Coring Bit (#3724, Figure 8) from Scorpion Engineering and the QD Tech Hybrid Coring Bit (#90513, Figure 7). The GeoSet bit was successfully used to core through approximately 3 meters of ice with layers of the granite rubble. Ice core quality was reasonably good. ROP was limited to 2 – 3 mm/s at 300 RPM, with pump position 3.

Figure 8: GeoSet Diamond Bit used for Mixed Ice/Rock Coring

The QD Tech Hybrid Coring Bit was used to core through approximately 1.5 meters of ice with layers of granite rubble. The bit easily penetrated at 2 - 3 mm/s (300 RPM, pump pos. 5) with 20-40 psi registering on the gauge throughout the run. Very few ice chips and no rock cuttings were recovered. Only a small amount of ice and rock rubble was recovered. There were definite indications of melting and refreezing. The bit was extremely worn from granite/concrete coring before the attempt at mixed ice/rock coring (no clearance angle remained) which likely caused the bit to penetrate mostly by melting and tumbling granite chunks ahead of it. A large amount of sand-size rock cuttings and some uncut granite chunks were recovered on a subsequent run with the GeoSet Coring Bit that ended in solid concrete at the bottom of the test hole.

The same Lower Reaming Shell, Figure 9, used with the Ice Bit was used when coring mixed ice and rock. It showed significant signs of wear and some tendency to clog with ice/rock cuttings and refrozen water.

Figure 9: Lower Ice Reaming Shell/Centralizer

Coring Bits - Conclusions

The PCD Coring Bit from Scorpion engineering produced good quality ice core and can penetrate softer rock or sediment successfully. Both the GeoSet Coring Bit from Scorpion Engineering and the QD Tech Hybrid Coring Bit can successfully core mixed ice and granite. A separate reaming shell for mixed ice/rock coring is likely needed. The #12 matrix Impregnated Coring Bit from Scorpion produced excellent quality granite core.

8.5. Display Box

Figure 10 shows an overview of display wiring. A detailed electrical schematic of the entire drill system is shown in 8323-0021 ASIG Equipment Assembly Drawings.

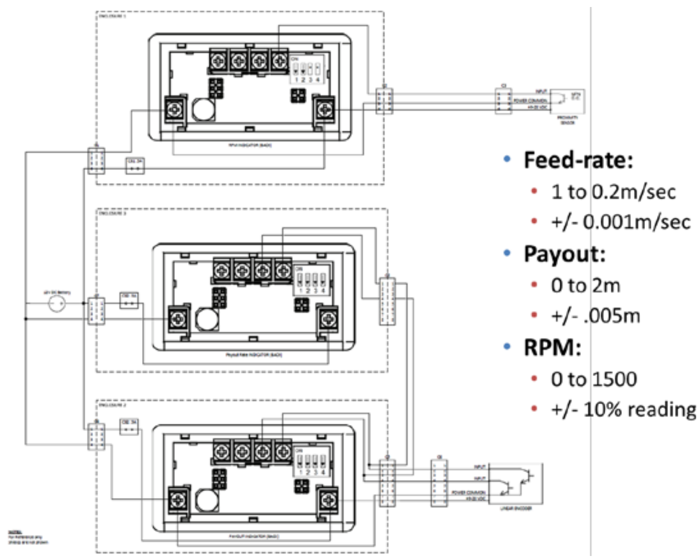


Figure 10: Display Wiring Schematic

8.6. Site and Tent

The figure below provides an overview of the site layout for the ASIG Drill System. Detailed instructions for rig and tent assembly are provided in 8323-0020 ASIG Equipment Manuals.

Important Notes:

- *Engines are located outside the drill tent to help mitigate the risk of carbon monoxide poisoning from exhaust fumes. It is also important to address this risk when using the pop-up maintenance tent for engine repair. Use of a properly functioning CO detector and exhaust hose is required when operating engines in the maintenance tent. The manual for the CO detector is provided in* 8323-0020 ASIG Equipment Manuals.

- *Hydraulic hose routing must be done with care to avoid damage to hoses during operations. Hydraulic hoses running on firn or ice should be thermally insulated to prevent them from melting into the ice (i.e. dunnage or packing foam). Additionally, dunnage or plywood should be used to prevent abrasion of console-to-mast hoses running on the footer grating.*

- *Wireline mast must be stabilized with guy lines to address potential side loads.*

Figure 11 shows the schematic of the 12AWG grounding wires included for field deployment. Note: 120VAC engine block heaters also ground the generator to the engines being heated. The fuel and drill fluid tanks will be grounded with clip-on ground straps.

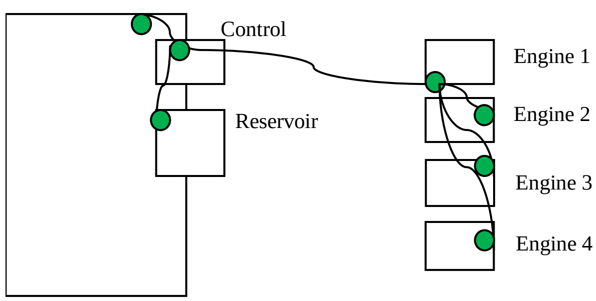


Figure 11: Grounding Schematic

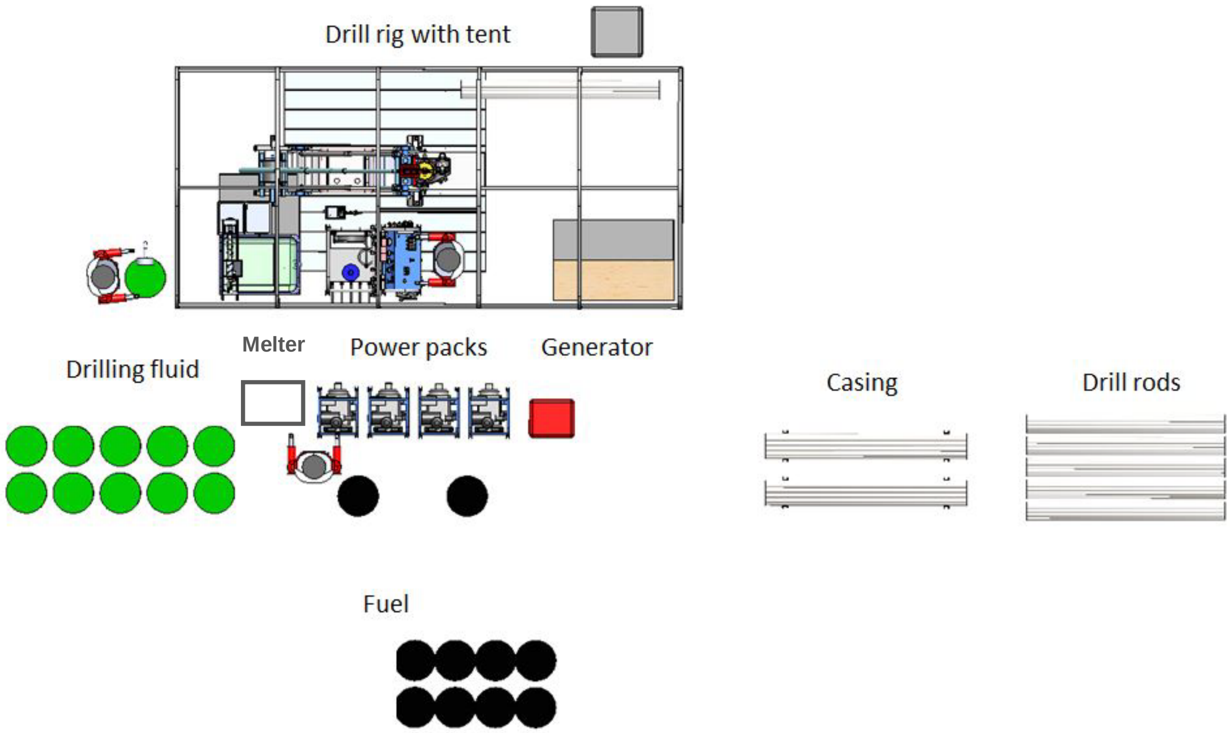


Figure 12: ASIG Drill System Site Layout

9.0 PRE-SHIP CHECKLIST

9.1. Verify shipping inventory 8323-0023 ASIG Equipment Lists to be sure all equipment and spares are shipped and required components are requested on the SIP.

9.2. Inspect and clean components as necessary to assure they are in good working order and all safety and identification labels are still intact and legible.

9.3. Complete maintenance per 1) rig manual, 2) daily checklist and 3) site checklists (Appendix A) as applicable.

9.4. Power rig and operate sub-systems to verify proper operation.

9.4.1. Feed/Pull-back

9.4.2. Head and Foot Clamps

9.4.3. Head Rotation with Torque Range

9.4.4. Winch Pay-In/Pay-Out

9.4.5. Filtration Auger

9.4.6. Mud Pump (operate with fluid)

APPENDIX A: MAINTENANCE CHECKLISTS

ASIG Preventive Maintenance Checklist		
DAILY CHECKS	**DATE : _______**	
ITEM	**ACTION**	**INITIALS**
TOP DRIVE		
Fasteners	Inspect top drive for loose fasteners	
Lubrication	Grease (refer to manual for grease points)	
Leaks	Inspect for hydraulic leaks	
Belt	Check tension	
Chuck	Inspect for damage and proper assembly	
FOOT CLAMP		
Fasteners	Inspect for loose connections	
Lubrication	Grease (refer to manual for grease points)	
Leaks	Inspect for hydraulic leaks	
FLUID CIRCULATION / FILTRATION		
Water Pump	Inspect for leaks/damage and check oil level	
Filters	Clean as needed	
Hoses	Inspect drill fluid hoses for leaks/damage	
Fluid Level	Verify a minimum of 3" drill fluid is available in reservoir	
TOOLS		
Tools	Inspect for damaged/missing tools	
DOWNHOLE TOOLS		
Fasteners	Check for any loose connections	
Water swivel	Ensure free rotation, check seals, grease	
Water swivel Tether	Anti-whip tether properly attached between swivel and hose	
Barrels	Inspect for any dents or thread damage	
Bits	Inspect for excessive wear, replace as needed	
MAST / TOWER		
Crown sheave	Inspect for damage and ice buildup	
Components	Inspect for damage/fluid and ice buildup	
Strut Arms	Inspect for damage and proper assembly	
RIG BASE / FOOTING		
Stability	Check stability, leveling, and anchoring	
Fasteners	Inspect for any loose connections	
DRILL TENT		
Frame and Fabric	Inspect for damage	
Snow / Ice	Remove any significant drifting	
Anchoring	Check guy lines, pickets, anchors, and berms	

ASIG Preventive Maintenance Checklist		
DAILY CHECKS	**DATE : _______**	
ITEM	**ACTION**	**INITIALS**
ENGINES		
Fuel	Check drum level and fill as needed	
Battery	Check cable connections	
Snow / Ice	Remove any drifted snow or ice accumulation	
Coolant	Verify correct fluid level	
Oil	Check level	
Fuel Filter	Drain water	
Fuel Lines	Inspect for damage	
Air Filter	Inspect	
Belts	Inspect	
HYDRAULIC TANK		
Hydraulic Fluid	Check level and fill as needed (>3/4 full)	
HYDRAULIC PUMPS		
Fasteners	Inspect for any loose connections	
HYDRAULIC HOSES		
Hoses	Inspect hydraulic hoses for leaks/damage	
Connections	Inspect and tighten as needed	
CASING PACKER		
Pressure	Verify casing inflation pressure	
WIRELINE WINCH		
Grease	Add grease to bearings (see MPP Manual)	
Wire Rope	Inspect for damage	
GENERATOR		
Generator	Inspect fluid levels, connectors, general condition of 120V generator if used	
SITE		
Exits	Verify two functional and unobstructed exits	
Fluids	Address any buildup of fuel or drilling fluid	
Combustibles	Combustibles disposed of properly	
Clean-up	Aisles clear; extraneous equipment, material put away	
Wiring	Inspect ground and electrical wiring and connectors	
Anchors	Inspect rig anchors for visible damage or loosening	
COMMENTS:		

ASIG Preventive Maintenance Checklist			
Set-up and Start-up Checks **(to be performed in addition to daily checks at each new drilling location)**			
ITEM	**ACTION**	**DATE**	**INITIALS**
TOP DRIVE			
FOOT CLAMP			
CONTROL SYSTEM			
E-Stop	Verify function		
DRILL TENT			
Structure and fabric	Inspect for damage		
HYDRAULIC HOSES / FITTINGS			
FLUID CIRCULATION / FILTRATION			
Fluid hoses/plumbing	Check for damage and leaks		
Pump check-valve	Check for appropriate operation		
SAFETY EQUIPMENT			
Batteries	Check for dead/leaking batteries		
Lifting straps	Inspect for damage/wear		
MAST / TOWER			
Grounding	Verify ground continuity		
Tower assembly	Inspect for damage		
Tower fasteners	Check for loose bolts/torque as needed		
Crown sheave	Verify smooth rotation; check before cable is connected		
WINCH/LEVEL WIND			
Winch system	Inspect for damage		
Winch drum	Check torque on drum flange bolts		
Winch motor	Inspect for functionality		
PILOT HOLE / CASING SETTING			
Fasteners	Check for any loose connections		
DOWNHOLE TOOLS			
RIG BASE / FOOTING			
ENGINES			
Anti-freeze	Verify Level and approximately 60% concentration for storage to -52C (-62F).		
COMMENTS:			

Appendix B: ASIG System Performance Data
(Based on 2016 NA Testing)

Pump Speed Data:

Table 1: Pump Speed vs. Flow-rate
Calculated flow rates based on 0.0359 gal/rev pump specification.
Measured flow rates are based on time to fill a 4-gallon container.

Rig Pump Speed Setting	Measured Pump Speed (RPM)	Calculated Pump Flow-rate (GPM)	Measured Pump Flow-Rate (GPM)
1	-	-	-
2	69	2.5	2.2
3	-	5.9	-
4	261	9.4	8.6
5	-	11.3	-
6	367	13.2	10.9
7	-	14.1	-
8	465	15.1	15.0
9	477	17.1	18.5

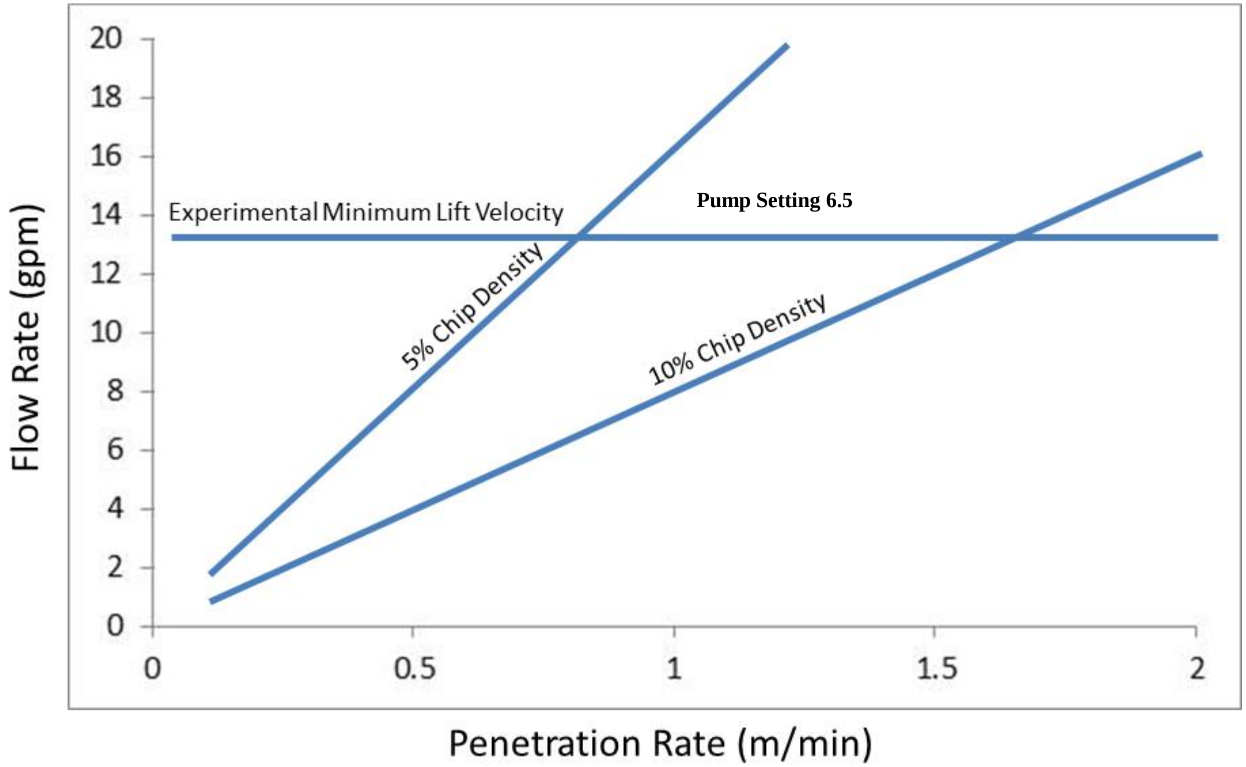


Figure 13: Fluid Flow Limits for Ice Chips in Reverse Circulation.

Testing was initially performed with a pump speed setting of 3.5 providing a calculated flow-rate of 8gpm (30 L/min). This value was selected for penetration rates of 0.5 to 1m/min based on a rule-of-thumb of 5-10% chip density. This also provided a flow velocity equivalent to 3 times the slip rate of ice chips up to 5mm diameter as measured in the IDP lab. However, clogging in the borehole and at the water swivel resulted repeatedly at this setting.

A correlation to results of the Rapid Access Ice Drill (RAID) testing with a flow-rate of 20gpm (76 L/min) at 1.5 times the ASIG annular cross-section suggested a much higher flow rate of 10-15gpm (38-57 L/min) would be required. Figure 13 shows this higher flow-rate required to lift ice chips far exceeding that required to achieve the chip density target of 5-10%. Subsequent testing confirmed effective chip transport at 13gpm (49 L/min) for penetration rates up to 1.9m/min.

Measured pump pressures at this flow rate were approximately 15 to 20psi at 13m depth with occasional spikes to 40psi. The fluid model provided by A. Eustes, IDP-Dartmouth, predicts a 13psi pump pressure at 13gpm /13m depth and does not account for transient pressure spikes. Results from greater drilling depths will be required to validate or further refine the model but these initial results show reasonable correlation.

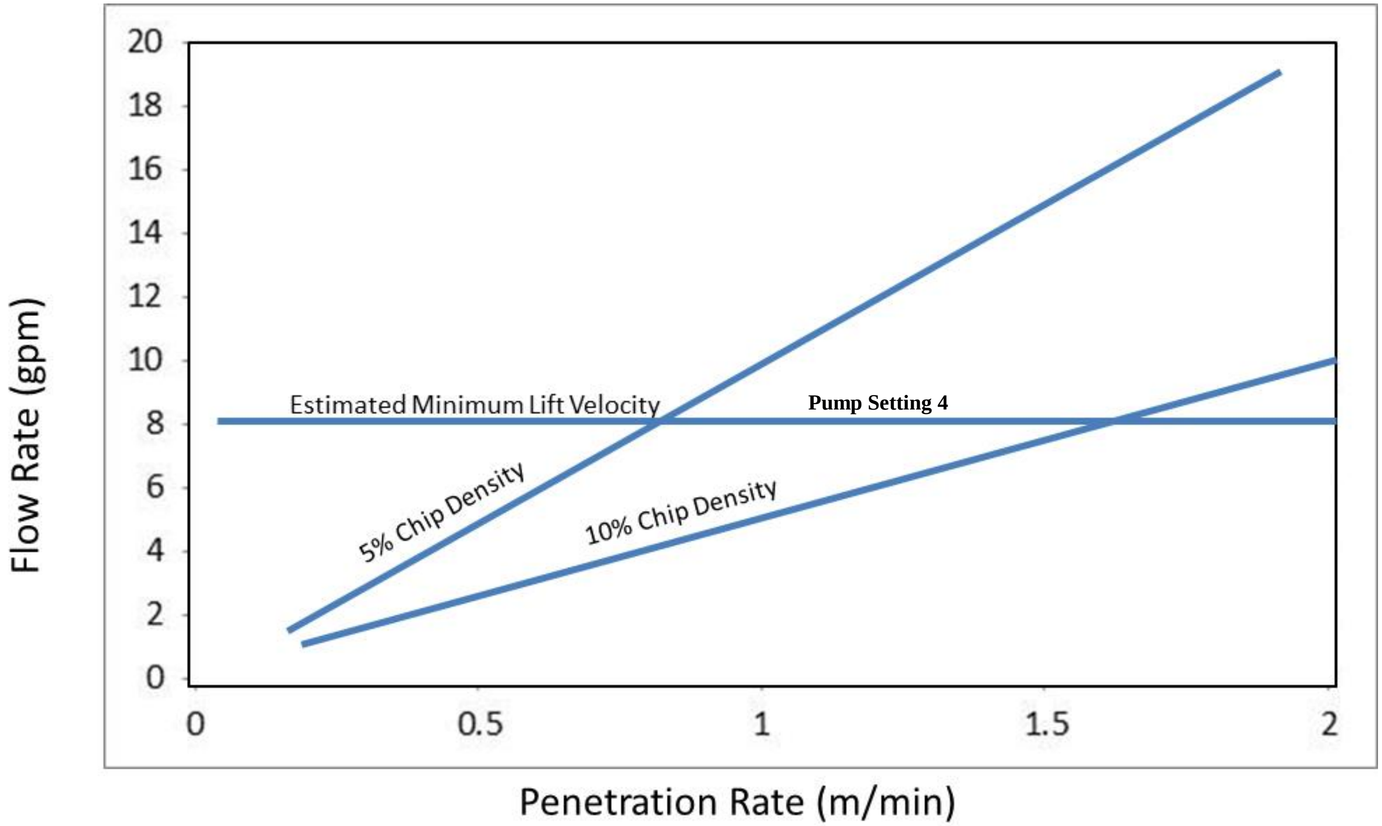


Figure 14: Fluid Flow Limits for Ice Chips in Normal Circulation

Based on a correlation to results above, the flow-rate required for coring ice in conventional circulation is shown in Figure 14. The area of the annulus between the bore wall and drill rod is 52% of the internal rod area, so the slip-rate limit for ice-chips in coring in conventional circulation is reduced by this factor to approximately 8gpm (30 L/min).

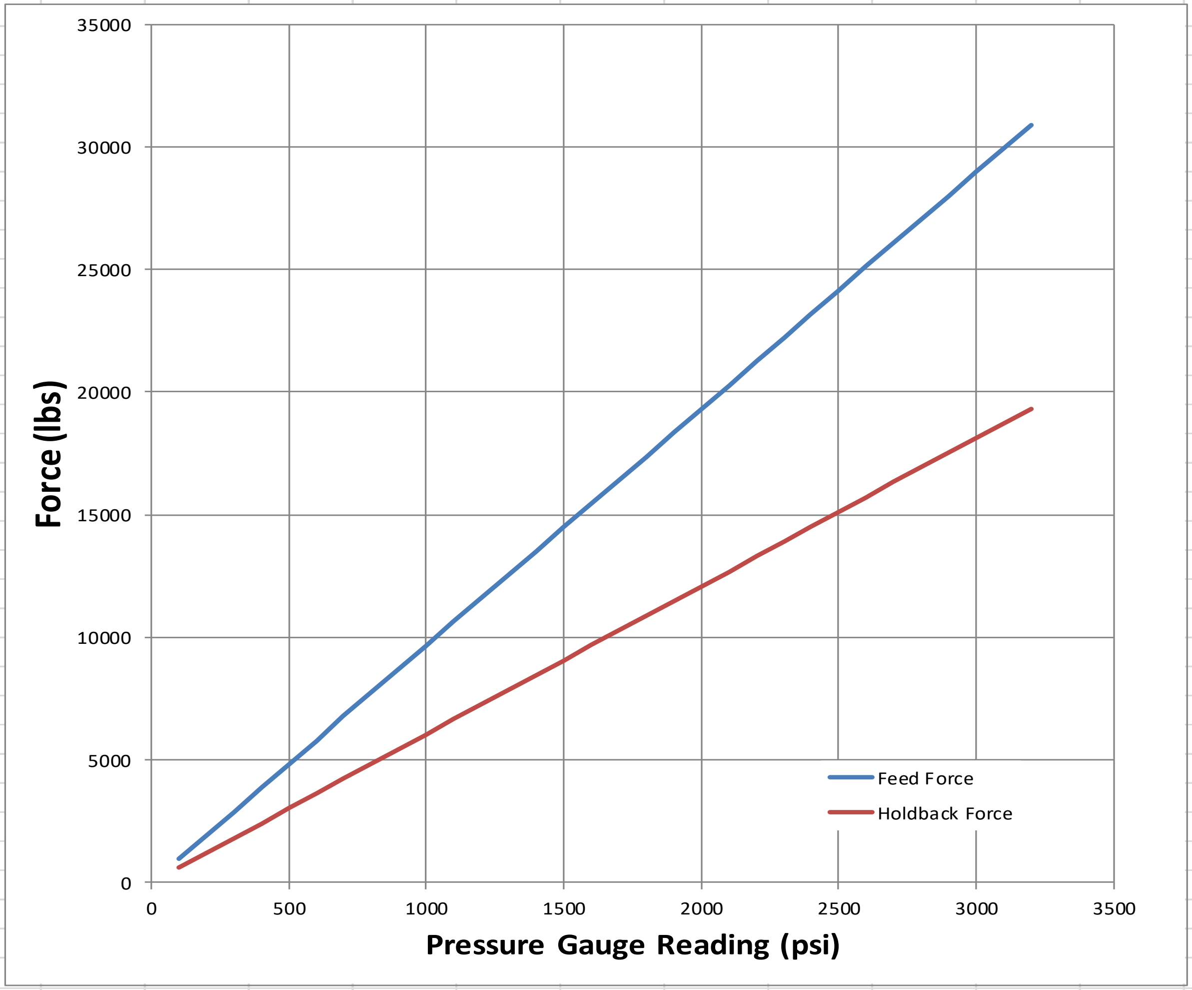
Rock and Sediment Coring (Normal Circulation):

Flow rates required to maintain target chip densities for rock and sediment coring are the same as those for ice shown in Figure 14 above. Slip rates, however, are much larger for rock. Slip rates measured for 1 to 3mm diameter granite chips in -30°C Isopar K were 2 to 6 times those measured for ice. A direct correlation to results above for ice would predict that 18-54gpm (68-204 L/min) would be required to lift rock chips 1 to 3mm in diameter. The ASIG pump has been selected with a maximum flow rate of 20gpm (76 L/min) as flow rates above this exceed allowable ice formation pressures even at very shallow depths. As a result, larger rock particles like these would not be expected to transport well.

Rock coring testing was performed with 9gpm flow-rate resulting in pressures of 60-90psi. Powered rock from a diamond impregnated bit did transport well. Larger particles of rock generated particularly in sediment drilling did not transport and were only recovered from the bottom of the hole on top of the core. See Figure 15. Through more experience with the ASIG Drill in the field, a balance will need to be achieved between high-flow rates required to lift larger rock chips and formation pressure limits.

Figure 15: Rock Chips from Sediment Drilling
These larger granite particles created during sediment drilling did not transport to the filtration system but were recovered in the core barrel.

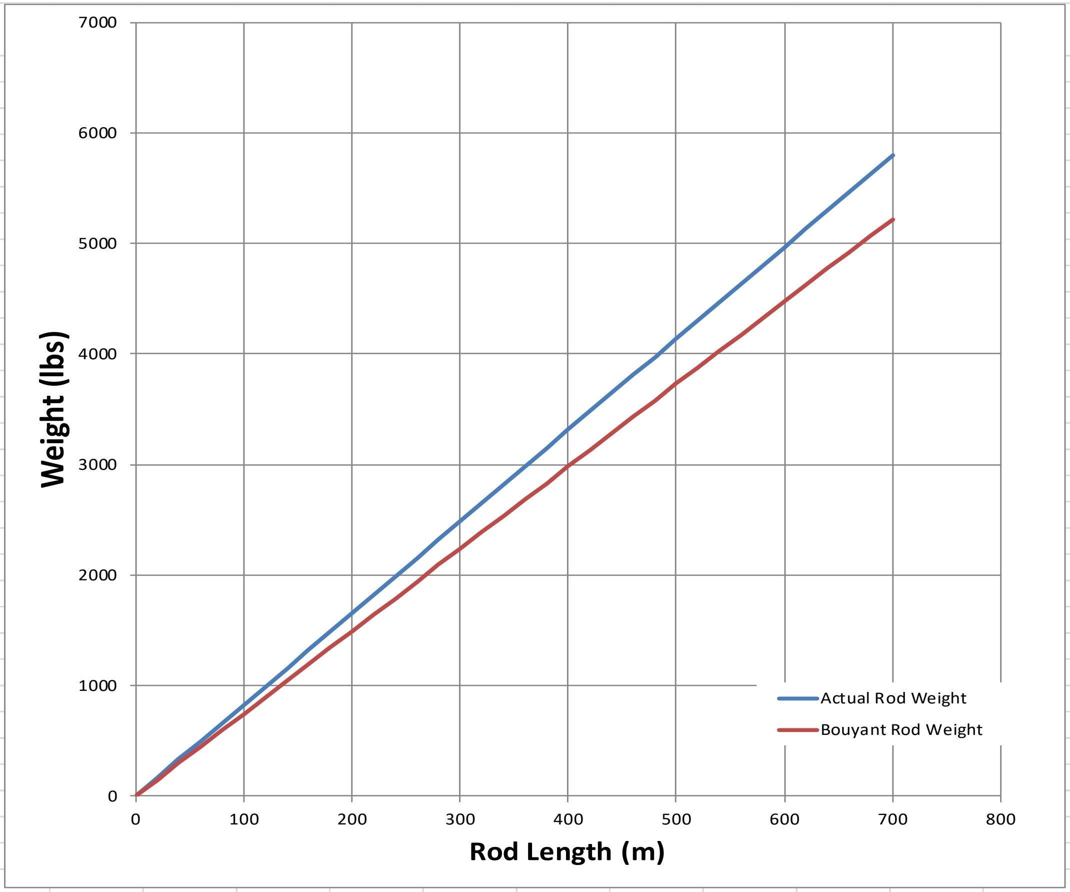
2-CYLINDER FEED AND HOLDBACK FORCES



Pressure Reading	Feed Force	Holdback Force
psi	lb	lb
100	966	604
200	1931	1208
300	2897	1813
400	3862	2417
500	4828	3021
600	5793	3625
700	6759	4229
800	7724	4834
900	8690	5438
1000	9655	6042
1100	10621	6646
1200	11586	7250
1300	12552	7855
1400	13517	8459
1500	14483	9063
1600	15448	9667
1700	16414	10271
1800	17379	10876
1900	18345	11480
2000	19310	12084
2100	20276	12688
2200	21241	13292
2300	22207	13897
2400	23172	14501
2500	24138	15105
2600	25103	15709
2700	26069	16313
2800	27034	16918
2900	28000	17522
3000	28965	18126
3100	29931	18730
3200	30896	19334

Figure 16: Feed and Hold-Back Forces

ROD WEIGHT SANDVIK WL56



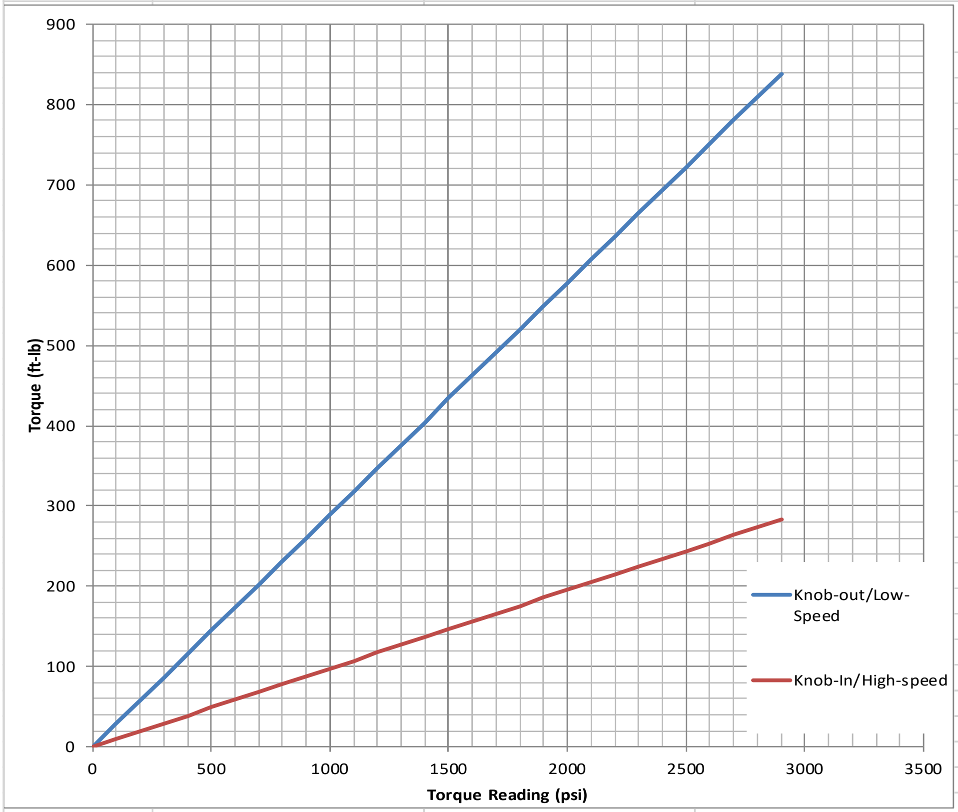
Depth	Actual Rod Weight	Bouyant Rod Weight
m	lb	lb
0	0	0
20	166	149
40	331	298
60	497	447
80	662	597
100	828	746
120	994	895
140	1159	1044
160	1325	1193
180	1490	1342
200	1656	1491
220	1822	1641
240	1987	1790
260	2153	1939
280	2318	2088
300	2484	2237
320	2650	2386
340	2815	2535
360	2981	2685
380	3146	2834
400	3312	2983
420	3478	3132
440	3643	3281
460	3809	3430
480	3974	3579
500	4140	3729
520	4306	3878
540	4471	4027
560	4637	4176
580	4802	4325
600	4968	4474
620	5134	4623
640	5299	4773
660	5465	4922
680	5630	5071
700	5796	5220
Isopar K ~800kg/m3		

Figure 17: Rod Weight Sandvik WL56

ROTATION HEAD PERFORMANCE

Rexroth AA6VM160HD2	Torque Range Knob Out (rpm/max ft-lb)*	Torque Range Knob In (rpm/max ft-lb)*
1 Engine*	38 / 838	100 / 283
2 Engines*	200 / 838	500 / 283
3 Engines*	325 / 838	900 / 283
4 Engines*	450 / 838	1300 / 283

*approximate values; max torque at 2900psi max operating pressure



Torque psi	HighSpeed ft-lb	LowSpeed ft-lb
0	0	0
100	10	29
200	20	58
300	29	87
400	39	116
500	49	144
600	59	173
700	68	202
800	78	231
900	88	260
1000	98	289
1100	107	318
1200	117	347
1300	127	376
1400	137	405
1500	146	433
1600	156	462
1700	166	491
1800	176	520
1900	185	549
2000	195	578
2100	205	607
2200	215	636
2300	224	665
2400	234	694
2500	244	722
2600	254	751
2700	263	780
2800	273	809
2900	283	838

Figure 18: Rotation Head Performance